Vertical distribution pattern of naidids in granular activated carbon filters and potential technology to control their penetration risk

Xiao-Bao Nie, Yun-Zi Tang, Chang-bo Jiang, Yuan-Nan Long, Pan-Pan He and Chao Xu

ABSTRACT

Aquatic worms propagated in granular activated carbon (GAC) filter has become a troublesome problem for drinking water supply. This study investigated the vertical distribution patterns of naidids in GAC filter beds and assessed the effect of an additional sand bed, located below the GAC bed, in preventing naidids from being present in effluent. The results indicated that the vertical distribution data of naidids in the GAC filter bed were well fitted by a Gaussian distribution, and the location of peak population density was mainly affected by downward flow. Backwashing experiments revealed that additional pressure air scouring shifted the distribution pattern of naidids in the GAC filter bed, resulting in a significant enhancement in naidid removal efficiency. Additionally, the addition of a sand bed exhibited pronounced interception and inactivation effects on naidids, suggesting that it may be a very promising technology for preventing naidids propagated in GAC filters from being present in the effluent.

Key words | backwashing, distribution pattern, GAC filter, naidids, sand bed

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INTRODUCTION

Aquatic worms such as oligochaetes, nematodes and the larvae of some insects, e.g. chironomids, are cosmopolitan invertebrates and often the main benthic or staggered planktonic macro-organisms in source water (Lin & Yo 2008; Luoto 2011). These worms may penetrate through water treatment units and present in drinking water distribution systems due to their high stretching capacity (Bichai *et al.* 2009; Christensen *et al.* 2011). Although there are no indications that these worms pose a threat to public health (Van Lieverloo *et al.* 2012), their presence is not appreciated, as most people associate the organisms with poor sanitation (Bichai *et al.* 2010).

Many drinking water plants in developing countries have recently implemented granular activated carbon (GAC) filters to guarantee drinking water quality (Kennedy *et al.* 2015). However, previous studies have shown that the GAC filter itself could be associated with drinking water contamination as aquatic worms have been detected in the GAC filters (Li *et al.* 2010; Wang *et al.* 2014). To date, although aquatic worms are observed to propagate excessively in GAC filters (Scheriber *et al.* 1997; Beaudet *et al.* 2000; Li *et al.* 2010), little is known regarding their distribution pattern in GAC filters.

Currently, the main approaches proposed for the removal of aquatic worms include disinfection strategies and the optimization of filtration (Nie *et al.* 2010). However, both approaches are deemed to be unsuitable for GAC filters. For example, disinfectants cannot only inactivate

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aquatic worms, but also kill functional microorganisms in the GAC filters and destroy the pore structure of activated carbon. Although increasing backwashing strength enhances the removal effectiveness of aquatic worms, very high backwashing strength is prohibited to prevent the loss of filter media.

In south China, naidids have recently been detected in GAC filters and drinking water distribution systems. The objectives of this study were to investigate the distribution patterns of naidids in GAC filters, and to assess the effect of an additional sand bed located below GAC filter media in preventing naidids from presenting in effluent. An additional goal was to assess the effect of backwashing of GAC filter on the removal efficiency of naidids.

MATERIALS AND METHODS

Pilot experimental device and materials

Two sets of GAC filter devices were set up in Bijiashan WTP, one of the major drinking water treatment plants in Shenzhen city, China. Both devices consisted of four GAC filter columns with the same size and structure, and each column was made up of 15 cylinders (diameter 50 mm) joined to each other by plastic joint flanges (Figure 1). The height of the top and bottom cylinders were 1,000 mm and 200 mm respectively, compared to the 100 mm height of the other cylinders.

In device #1, columns were filled from the bottom to the top with graded gravel up to a height of 200 mm, and GAC (collected from the GAC filter of Bijiashan WTP) up to a height of 1,000 mm, while sand ($d_{10} = 0.58$ mm; $K_{80} = 1.4$) was located between the graded gravel and the GAC in device #2, up to a height of 300 mm. Columns were made of Lucite, and were fed with effluent from ozone contact tanks in Bijiashan WTP. Naidids were collected from backwashing water of GAC filter in Bijiashan WTP.

During the filtration, the water outlets of filter columns were wrapped with 35 μm nylon meshes to intercept the worms presenting in the effluent. The mesh was replaced once per day and the number of worms intercepted was recorded.

Experimental approach

Three respective series of experiments were performed in device #1 to investigate the effects of filtration rate, filtration cycle length and backwashing mode on the spatial distribution pattern of worms in GAC bed. Filtration rates included 6 m/h, 8 m/h, 10 m/h and 12 m/h, and filtration cycle lengths were set at 7 d, 10 d, 14 d and 18 d. Once filtration cycle length was reached, backwashing was conducted, and the three backwashing modes included (i) mode 1: backwashing 10 min by water fluidization alone with active carbon bed expansion of 20% (1,180 mL/min), (ii) mode 2: backwashing 10 min by water fluidization alone with active carbon bed expansion of 40% (1,550 mL/min), and (iii) mode 3: combination of pressure air scour (2,000 mL/min) and water fluidization (1,180 mL/min) 2 min followed by backwashing 8 min by water fluidization alone (1,180 mL/min). Another series of experiments were performed in device #2 to assess the effect of an additional sand bed below the GAC filter media on controlling the penetration risk of naidids.

For each column in device #1, 10 L of distilled water containing 2,000 worms were added. Both worms and water were divided into ten equal parts, and all parts were added in batches at a time interval of half an hour. For device #2, 1 L of distilled water containing 200 worms was added on the interface between active carbon and sand, followed by the addition of active carbon on the sand bed after half an hour, to stimulate a penetration rate of 10% for worms in a GAC bed.

When the desired filtration time or backwashing time was reached, the GAC filter columns were drained and dismantled. Filter media in various 100 mm cylinders were removed individually and inverted into the correspondingly labelled plastic containers.

The summary of tests and the experimental conditions are presented in Table 1.

Enumeration of the naidids retained in the GAC filter media

The GAC filter media in each labelled plastic container were divided into 10 equal fractions. Each fraction was transferred into a 1 L beaker. Then, 500 mL tap water was

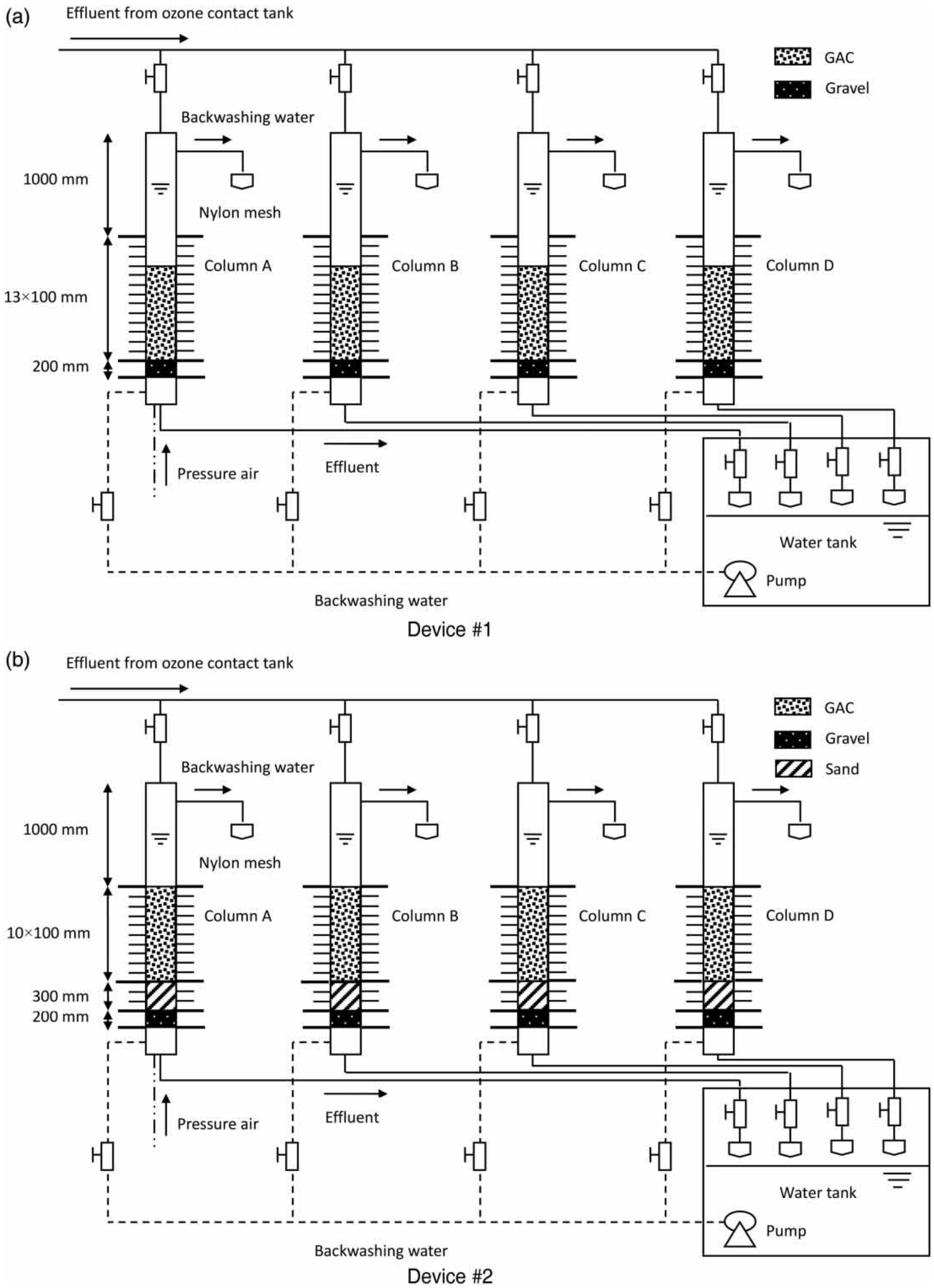

Figure 1 | Schematic overview of the GAC filter device #1 and device #2.

added into each beaker, and the beaker was shaken vigorously for 2 min to promote the detachment of naidids from the media grains. This process of shaking was repeated five times with the tap water being replaced each time. All tap water was collected and filtered through a 35 μm net to retain the invertebrates. Samples were then fixed with 4% formaldehyde. For naidid enumeration, the samples were transferred onto a counting plate and allowed to settle for 5 min. The entire counting chamber was scanned and the naidids were enumerated.

Table 1 | Summary of tests and experimental conditions

			Filtration operation conditions			Worms added	
Test	**Column**	**Temperature (°C)**	**Rate (m/h)**	**Cycle length (d)**	**Backwashing mode**	**Number**	**Location**
FR-1	A of device #1	22–29	6	10	(i)	2000	GAC bed
FR-2	B of device #1	22–29	8	10	(i)	2000	GAC bed
FR-3	C of device #1	22–29	10	10	(i)	2000	GAC bed
FR-4	D of device #1	22–29	12	10	(i)	2000	GAC bed
FCL-1	A of device #1	22–29	8	7	(i)	2000	GAC bed
FCL-2	B of device #1	22–29	8	10	(i)	2000	GAC bed
FCL-3	C of device #1	22–29	8	14	(i)	2000	GAC bed
FCL-4	D of device #1	22–29	8	18	(i)	2000	GAC bed
BW-1	A of device #1	22–29	8	10	(iii)	2000	GAC bed
BW-2	B of device #1	22–29	8	10	(ii)	2000	GAC bed
BW-3	C of device #1	22–29	8	10	(i)	2000	GAC bed
SA-1	A of device #2	22–29	8	7	(i)	200	Interface of GAC and sand
SA-2	B of device #2	22–29	8	10	(i)	200	Interface of GAC and sand
SA-3	C of device #2	22–29	8	14	(i)	200	Interface of GAC and sand
SA-4	D of device #2	22–29	8	18	(i)	200	Interface of GAC and sand

Enumeration of naidids in effluent and backwashing water

Naidids occurring in the effluent or backwashing water were intercepted by the nylon mesh. Upon removal from the outlet of the filter column, the nylon mesh was placed into a 250 mL beaker with 200 mL of sodium hypochlorite solution (0.2 mg/L). This soaping process lasted for 2 min, after which the nylon mesh was removed following rigorous shaking three times. Due to the pronounced decreased activity induced by the oxidation of sodium hypochlorite, naidids sank to the bottom of beaker, and were transferred to Petri dishes using a dropper and then enumerated using a high-powered magnifying lens.

Analytical methods

Naidid population density in the water or filter media was expressed as N/V, where N is the number of naidids counted in water or filter media and V is the volume of water or filter media. The removal efficiency was expressed as $N_1/(N_1+N_2)$, where N_1 and N_2 are the number of naidids counted in the backwashing water and GAC filter media after backwashing. All experiments were repeated three times. Statistical analyses were performed using Microsoft Excel and Origin 9.1.

RESULTS

Spacial distribution pattern of naidids in the GAC filter column

The vertical distribution of naidids in the GAC filter bed under various filtration rates illustrated that all distribution profiles possessed the same trend in variation, which was well described by a Gaussian distribution (Figure 2(a)). The depths at which the peak population density occurred increased with the enhancement of filtration rate. Additionally, the value of the peak population density decreased with the enhancement of filtration rate.

It appears that for filtration cycle lengths of 7 d and 10 d, a Gaussian distribution curve can be applied to the data (Figure 2(b)), with the maximum population density occurring at the layer of 30–40 cm. In contrast, the distribution

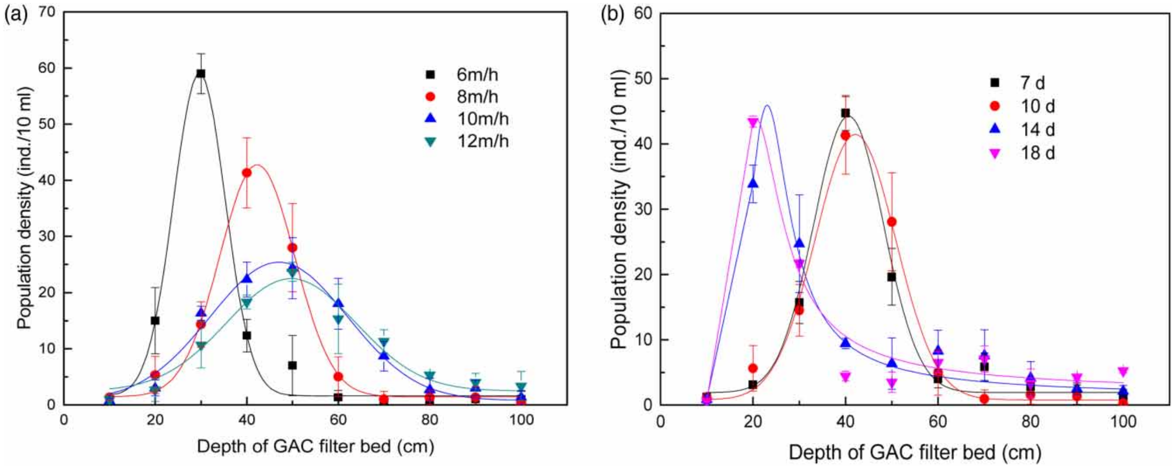

Figure 2 | Vertical distribution profiles of naidid densities in GAC filter bed at various filtration rates with filtration cycle length of 10 d (a) and at various filtration cycle lengths with filtration rate of 8 m/h (b).

curves of 14 d and 18 d exhibited a similar two-stage feature, characterized by a fast linear increase until peak population density was reached, followed by a decrease in the form of a power function.

Removal efficiency of naidids under different backwashing modes

The removal efficiencies of naidids under mode 1, mode 2 and mode 3 were 32.7 ± 6.0%, 57.2 ± 8.2% and 80.5 ± 2.6%, respectively (Figure 3(a)). Statistical analysis indicated a significant difference occurred between any two backwashing modes ($P < 0.05$), suggesting both active carbon bed expansion and pressure air scouring significantly affected the removal efficiency of naidids.

The vertical distribution patterns of naidids in GAC filter bed before and after backwashing are presented in Figure 3(b). Mode 1 and mode 2 were well fitted to a Gaussian distribution, and the peak population densities were both located at a depth of about 40 cm. Figure 3(b) also indicated the linear fit curve for the data under backwashing mode 3. Compared to mode 1 and mode 2, the additional pressure air scouring resulted in a further decrease in population density in almost all layers.

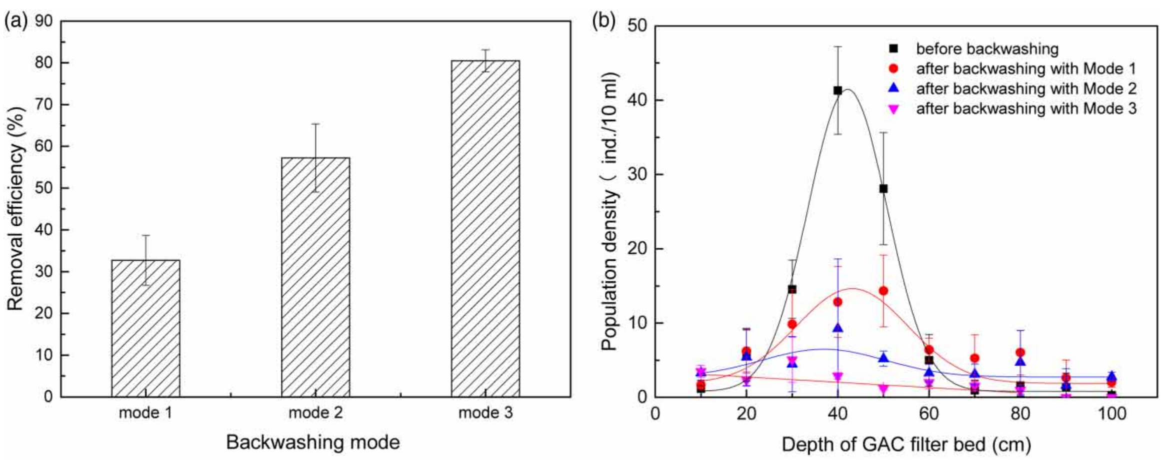

Figure 3 | Removal efficiency of naidids in the GAC filter under various backwashing modes (a) and vertical distribution profiles of naidid densities in the GAC filter bed before and after backwashing with various modes (b).

Notably, no worms were detected in the bottom 20 cm under mode 3.

Interception effects of an additional sand bed

Once an additional sand bed was introduced below the GAC filter bed, no worms were detected in the effluent under the various filtration cycles, despite that the sand bed height was only 300 mm. Surprisingly, some dead worms appeared in the sand bed. As a result, we decided to categorize the worms detected in the sand bed into living and dead worms, and defined the worm inactivation rate as $(N_0 - N_3)/N_0$, where N_3 is the number of living worms detected in sand bed and N_0 is the number of worms added in device. As depicted in Figure 4(a) and 4(b), at a filtration cycle length of 7 d the majority of living and dead worms were observed within the depth range of 5–15 cm. However, there were hardly any living worms in the sand bed once the filtration cycle length exceeded 10 d (Figure 4(a)). More dead worms were detected in the bottom layers of sand bed as the filtration cycle length was prolonged from 7 d to 14 d (Figure 4(b)), and almost no worms were detected in the sand bed under a filtration cycle length of 18 d. Both the total number of worms and the inactivation rate were significantly affected by the filtration cycle length ($P < 0.05$) and, as depicted in Figure 4(c), linear and exponential regression curves can be applied to the data of total number of worms and inactivation rate, respectively.

DISCUSSION

The distribution data at various filtration rates were well fitted to a Gaussian distribution, confirming the vertical random migration of naidids in the GAC filter bed. Meanwhile, the location where the peak population density occurred was characterized by a downward trend along with increasing filtration rate, suggesting that downward flow may be the major driving force for the vertical migration of naidids. Therefore, it can be speculated that the distribution pattern of naidids is determined by the

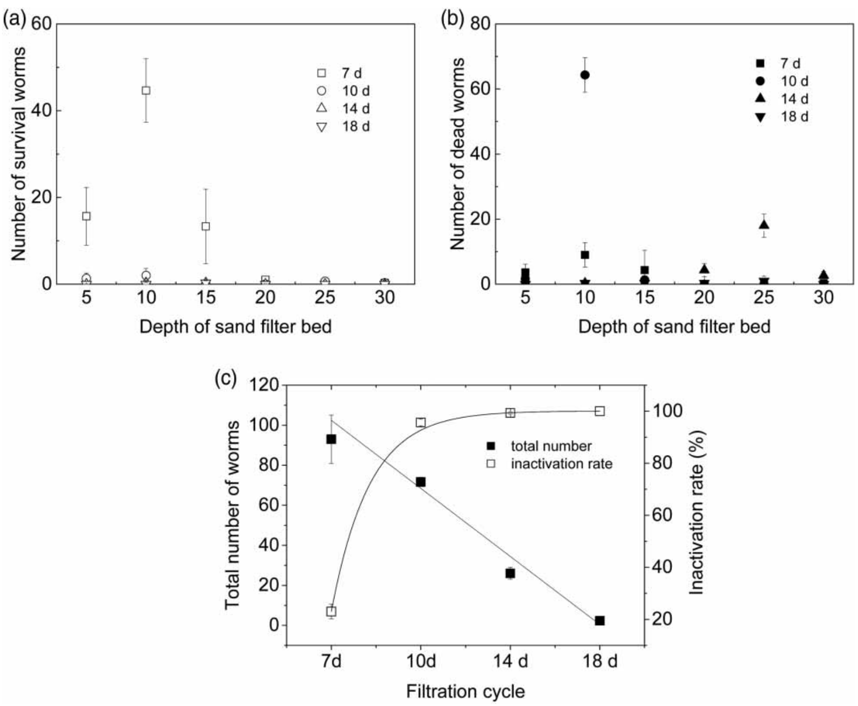

Figure 4 | Interception and inactivation effects of an additional 300 mm height sand bed on naidid in GAC filter. (a) Vertical distribution of living naidids in the sand bed, (b) vertical distribution of dead naidids in the sand bed, and (c) total number and inactivation rates of naidids under various filtration cycles. All experiments were performed at a filtration rate of 8 m/h.

combined effects of vertical random migration and downward flow in GAC filter.

Few naidids were detected in the top 10 cm, which may be explained by the fact that there is still some level of residual ozone in the top 10 cm of GAC filter bed. Lohwacharin *et al.* (2015) reported that the residual ozone concentration at the top of the GAC filter is within the range of 0.07–0.88 mg/L. Therefore, the adverse effect of residual ozone on organisms (Kim *et al.* 2003), may induce the naidids escaping to an adjacent layer of the filter bed, resulting in a marked drop in the population density of the top 10 cm.

Previous studies have reported that the GAC filter itself can be the origin of invertebrates (Scheriber *et al.* 1997; Weeks *et al.* 2007; Wang *et al.* 2014). This conclusion was confirmed by the fact in present study that the majority of worms were intercepted by the GAC filter. Since the GAC filter has been proven to be an ideal habitat for the rapid propagation of invertebrates, due to the presence of microbial biomass and detritus that invertebrates feed on (Weeks *et al.* 2007; Bichai *et al.* 2010; Yin *et al.* 2012), an increased interception efficiency may result in a higher naidid abundance in the GAC filter, and eventually a larger penetration risk.

For backwashing with water fluidization alone (mode 1 and mode 2), the adhesion of some naidids to the GAC filter media seemed to be sufficient to completely prevent themselves from being removal, as the distribution curves before and after backwashing showed the same trend. Once additional pressure air scouring was introduced, the removal efficiency increased significantly from $32.7 \pm 6.0\%$ (mode 1) to $80.5 \pm 2.6\%$ (mode 3), and the distribution pattern of naidids in the GAC filter bed shifted from a Gaussian distribution to a linear distribution. It is interesting to note that, despite the different invertebrates being backwashed in GAC filter, the removal of naidids closely matched some previous results (Scheriber *et al.* 1997; Weeks *et al.* 2007; Wang *et al.* 2014). For example, a removal efficiency of 58% for *Potamopyrgus jenkinsi* was reported by Weeks *et al.* (2007) when backwashed with water fluidization alone at 40% bed expansion, compared to $57.2 \pm 8.2\%$ for naidids in the current study. The removal efficiency of 80% for rotifers was reported by Scheriber *et al.* (1997) when backwashed with the additional pressure air scouring, compared to $80.5 \pm 2.6\%$ for naidids in the current study.

The effectiveness of a sand bed on the interception of invertebrates has been well documented by several studies (Scheriber *et al.* 1997; Adam *et al.* 1998). The present results confirmed this, as no naidids were detected in the effluent of GAC filter when an additional sand bed was introduced. Additionally, to the best of our knowledge, this is the first report on the inactivation effect of sand bed on invertebrates. Moreover, it is particularly surprising that along with the prolonged filtration cycle length, the total number of naidids decreased significantly and most naidids were lost at a filtration cycle length of 14 d and 18 d. We are unable to explain the absence of the naidids from the sand bed. Nevertheless, for naidids propagated in the GAC filter, the addition of a sand bed seems to be a very promising alternative technology to prevent their presence in effluent.

CONCLUSIONS

In this study, the vertical distribution data of naidids in the GAC filter bed were well fitted by a Gaussian distribution, and the location of peak population density was mainly affected by downward flow in the GAC filter. Both the characteristics of the Gaussian distribution in the GAC filter bed and the location of the peak population density were unaltered by backwashing with water fluidization alone. Once additional pressure air scouring was introduced, the distribution pattern of naidids shifted from a Gaussian distribution to a linear distribution, and removal efficiency increased significantly. An additional sand bed below active carbon bed appears to be a very promising alternative technology for preventing naidids' presence in effluent of GAC filter due to its pronounced interception and inactivation effect on naidids.

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